Non-chemistry coupled PM10 modeling in Chiang Mai City, Northern Thailand: A fast operational approach for aerosol forecasts

Ronald Macatangay

National Astronomical Research Institute of Thailand, Chiang Mai, Thailand

Gerry Bagtasa

Institute of Environmental Science and Meteorology, University of the Philippines, Diliman, Quezon City, Philippines

Thiranan Sonkaew

Faculty of Science, Lampang Rajabhat University, Lampang, Thailand

ronmcdo@gmail.com

Abstract. The Weather Research and Forecasting (WRF v. 3.7) model was applied to model PM10 data in Chiang Mai city for 10-days during a high haze event utilizing updated land use categories from the Moderate Resolution Imaging Spectroradiometer (MODIS). A higher resolution meteorological lateral boundary condition (from 1 degree to 0.25 degree) was also used from the NCEP GDAS/FNL Global Tropospheric Analyses and Forecast Grid system. A 3-category urban canopy model was also added and the Thompson aerosol-aware microphysics parameterization scheme was used to model the aerosol number concentrations that were later converted to PM10 concentrations. Aerosol number concentration monthly climatology was firstly used as initial and lateral boundary conditions to model PM10 concentrations. These were compared to surface data obtained from two stations of the Pollution Control Department (PCD) of Thailand. The results from the modeled PM10 concentrations could not capture the variability (r = 0.29; 0.27 for each site) and underestimated a high PM10 spike during the period studied. The authors then added satellite data to the aerosol climatology that improved the comparison with observations (r = 0.45; 43). However, both model runs still were not able to capture the high PM10 concentration event. This requires further investigation.

1. Introduction

Seasonal blankets of haze cover Northern Thailand every dry season, which occurs from around mid-February to May. One of the main causes of this haze is the burning of agricultural waste from highland corn farms from commercial contract farming, majority of which belong to agricultural conglomerate companies, which sources corn from Thailand, Myanmar, Laos and Vietnam. This crop change, from rice, is a response to the increasing demand for animal feed and rising corn prices. It also yields quick earnings as corn can be harvested in four months. Other causes include forest burning by hunters to displace wildlife, vehicular emissions, urban sprawl, rubbish burn, harvesting of exotic mushrooms and enhanced biogenic volatile organic carbon (VOC) emissions due to land use change and increased temperatures.

Aerosols and particulate matter (PM) are some of the components of haze. They affect both health and climate. PM10, or particulates having a size of < 10 μm, increases the risk of tracheal, bronchial and lung cancer. Thailand also sets lower air quality standards than global benchmarks for PM10 at 120 μg/m3. The World Health Organization sets it at 50 μg/m3.

Aerosols also affect the climate by modifying cloud microphysical properties producing increased cloud albedo (first indirect effect) and reduced cloud droplet size that may delay and reduce precipitation (second indirect effect) [1]. Related to the second indirect effect is the phenomenon called aerosol enhanced conditional instability. In a polluted environment, with strong absorbing aerosols, greater amounts of moist static energy build up during daytime because convection is largely suppressed by the aerosol-radiation interaction compared to the clean case [2].

In February 2011, Oanh et al. analyzed the effect of meteorology and emissions for Chiang Mai City, during the March 2007 haze episode [3]. In the study, it was pointed out that due to the lack of adequate emission input data for this region required for chemical transport modeling to predict the haze, the climatological approach in combination with statistics were utilized. However, in December 2011, Amnuaylojaroen et al. was able to use the California Mesoscale Puff (CALPUFF) model, driven by the Weather Research and Forecasting (WRF) model, to investigate PM2.5 distributions as well as the relative contribution of fine fraction (PM2.5) and coarse fraction (PM10-2.5) to PM10 fraction from forest fires in the Chiang Mai basin also for March 2007 [4]. In the study, it was found out that strong atmospheric stability and light low-level winds over Chiang Mai were the favorable conditions for particulate matter accumulation.

In this work, the Weather Research and Forecasting (WRF) model [5] version 3.7 was utilized with the Thompson aerosol-aware microphysics scheme [1] to simulate PM10 concentrations in Chiang Mai City without chemistry coupling to provide a more computationally cost-effective model setup for potential aerosol operational forecasts.

2. Methodology

2.1. Numerical Weather Prediction

In numerical weather prediction (NWP), physical laws of motion and conservation of energy that govern the evolution of the atmosphere (the dynamics) can be written into mathematical equations that can be solved numerically. For example,

$$\frac{\Delta A}{\Delta t} = f(A) \tag{1}$$

where $\Delta A/\Delta t$ is the change in a forecast variable, A, at a particular point in space with respect to time, t, and f(A) describes the physical processess that can cause changes in the forecast variable. Values of meteorological variables later in time are calculated by finding their initial values and then adding the physical forcing, f(A), that acts on the variables during the forecast period. This can be mathematically represented as,

$$A^{forecast} = A^{initial} + f(A)\Delta t \tag{2}$$

with the actual equations used are called the primitive equations. These equations dictate the forces or dynamics that give movement to air. It includes thermodynamic changes occurring in the atmosphere calculated from momentum, mass, energy and moisture conservation laws. Equally essential are: processes that occur at scales smaller than the model can resolve; energy, water and momentum exchanges between the atmosphere and other sources such as land, ocean and solar radiation; and cloud and precipitation physics. In NWP, the atmosphere is divided into smaller grid boxes (the size of which is called model resolution) where all these processes are calculated over an area which the model runs called the model domain [6].

2.2. Dynamical Downscaling and Model Parameterization

NWP models are usually driven by coarse spatial resolution (e.g. 1^o x 1^o) global climate models that are unable to resolve sub-grid scale features (i.e. clouds, topography, etc.). In order to perform regional and local impact studies, downscaling has to be performed. One form is dynamical downscaling, where output from the coarse resolution model is used to drive a higher spatial resolution model. One such model which can perform dynamical downscaling is the Weather Research and Forecasting (WRF) model. This is used in this study.

However, even when dynamical downscaling is performed, there are still small-scale atmospheric processes that NWP models cannot resolve. The model must therefore account for the aggregate effects of these small-scale processes. This is called parameterization [7]. Some of the physical processes that are typically parameterized by models are condensation, turbulence, phase changes, surface roughness and deep convection. In order to produce fast aerosol simulations, parameterizing microphysics processes are essential.

Microphysics refers to the amount, type, processes (e.g. phase changes) and interaction between different condensates or hydrometeors (e.g. water vapor, cloud, rain, etc.). In this study, the Thompson aerosol-aware microphysics scheme was used. It was first utilized to investigate the effects of aerosols on cloud development and precipitation. It incorporates the activation of aerosols as cloud condensation nuclei (CCN) and ice nuclei (IN). In order to decrease the computational burden and complexity, the specific aerosol types as well as the chemical composition of multiple aerosol categories were simply referred to as "water-friendly" aerosols, or N_{wfa} (hygroscopic aerosols) and as "ice-friendly" aerosols, or N_{ifa} (non-hygroscopic ice-nucleating aerosols). N_{wfa} is the sum of sulfates, sea salt and organic carbon which are related to PM10 concentrations.

Normally, PM10 modeling involves coupling to chemistry. However, coupling to chemistry proves to be computationally expensive as shown by the study of Wang et al. in 2010 wherein approximately 8000 computation hours per model month were needed [8]. This is due to the increased number of variables to simulate. It was also mentioned in [1], that the simplest WRF model with chemistry options available at that time increased the number of variables by over a factor of 2 massively impacting computer memory and time. This defeats the purpose of forecasting an event, which needs updating model runs for at least every 6 hours.

2.3.Initial and Lateral Boundary Conditions, Model Domains and Validation Sites

The model runs in this study used the NCEP GDAS/FNL 0.25 Degree Global Tropospheric Analyses and Forecast Grid lateral boundary conditions [9] with a 10 km outer domain (parent) covering most of Indochina and a 3.33 km inner domain (child) encompassing most of northern Thailand. WRF v. 3.7 was ran for the period of April 10-20, 2016 UTC coinciding with the time period before, during and after the Thai New Year. The Thai New Year, or Songkran, is a big event in Thailand with many tourists coming in to celebrate this holiday. It also coincides with the recurring biomass burning season in northern Thailand.

Since the validation sites for PM10 concentrations are in an urban environment and sensitive to surface winds, the MODIS land use dataset and a 3-categogy urban canopy model were utilized. The optimum cumulus parameterization obtained in [10], was also used. The rest of the parameters were kept at the WRF v. 3.6 defaults. The comparison sites for Chiang Mai city for PM10 concentrations are at the Pollution Control Department (PCD) air quality monitor stations located at the Chiang Mai City Hall and at the Yupparaj Wittayalai School.

Initial and lateral boundary conditions for the aerosol number concentrations were derived from multi-year (2001-2007) global simulations from the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model including mass mixing ratios of sulfates, sea salts, organic carbon, dust and black carbon with 0.5 deg longitude by 1.25 deg latitude grid resolution [1]. This is designated as the control run. In order to incorporate up-to-date aerosol emission data, aerosol number concentrations derived from the Moderate Resolution Imaging Spectroradiometer (MODIS), on board Terra and Aqua satellites, were added

to the aerosol climatology for the initial conditions. Aerosol number concentrations were then converted to PM10 concentrations using the method described by Mönkkönen et al. in 2004 [11]. This is designated as the experimental run.

3. Results and Discussion

After the simulations, the following model verification metrics [12] were used to assess the performance of the model: mean error, (multiplicative) bias, mean absolute error, root mean square error, mean squared error and correlation coefficient. A paired sample t-test (with 99% confidence interval) was also done to assess whether the performance between the control and the experimental model runs was significantly different.

In Figure 2, simulations using the 2001-2007 GOCART climatological and MODIS aerosol number concentration boundary conditions (referred to as "climatology" and "MODIS" hereafter, respectively) are compared to observations at the Chiang Mai city hall and at the Yupparaj Wittayalai PCD stations. The calculated model verification metrics are also shown in Table 1. For both sites, the MODIS model runs outperformed the climatology runs for all the verification metrics. A statistically significant difference was also obtained between the two datasets.

Table 1. Model verification metrics calculated after comparing the climatology and the MODIS model runs to PM10 observations at the Chiang Mai city hall and Yupparaj Wittayalai School PCD stations.

	Perfect Score	Chiang Mai City Hall		Yupparaj Wittayalai School	
		Climatology	MODIS	Climatology	MODIS
Mean Error [microgram/m^3]	0	-62.20	-52.57	-79.20	-69.24
(Multiplicative) Bias, Bias	1	0.49	0.56	0.41	0.48
Mean Absolute Error, MAE [microgram/m^3]	0	62.61	56.23	79.27	70.49
Root Mean Square Error, RMSE [microgram/m^3]	0	74.80	66.95	87.92	79.67
Mean Squared Error, MSE [(microgram/m^3)^2]	0	5595.70	4482.10	7729.90	6347.70
Correlation Coefficient, r	1	0.29	0.45	0.27	0.43
No. of Metrics Won		**0**	**6**	**0**	**6**

Model outputs using MODIS captured more the variability at the two sites (r = 0.45; 0.43) as compared to the climatology run (r = 0.29; 0.27). However, both model runs failed to capture the high PM10 episode that occurred between April 16 – 17, 2016. This would have to be investigated in future work.

4. Conclusion and Recommendations

Weather models nowadays are usually characterized as having high resolution, fast computational speeds, relatively accurate and fairly simple representations of the state of the atmosphere in terms of meteorological variables such as temperature, pressure, relative humidity, rainfall, wind speed and wind direction. However, when considering air pollution concentrations, one normally couples these weather models with chemistry modules. Chemistry-coupled weather models are also characterized as having high resolution, but they are normally slow, have moderate accuracy and complicated. This study came up with PM10 simulations with speeds comparable to weather forecasts. This was attained by avoiding chemistry coupling, but instead utilized an aerosol-aware microphysics scheme combined with up-to-date satellite information of aerosol number concentrations for its initializations. The model results fairly captured the variability in the observations, but had difficulty simulating certain high PM10 events. This has to be studied further.

References

[1] Thompson, G., and Eidhammer, T. (2014). A Study of Aerosol Impacts on Clouds and Precipitation Development in a Large Winter Cyclone. Journal of Atmospheric Sciences, 71, 3636–3658.

[2] Fan, J., Rosenfeld, D., Yang, Y., Zhao, C., Leung, L. R., & Li, Z. (2015). Substantial Contribution of Anthropogenic Air Pollution to Catastrophic Floods in Southwest. Geophysical Research Letters, 42(14), 6066–6075. http://doi.org/10.1002/2015GL064479

[3] Oanh, N. T. K., and Leelasakultum, K. (2011). Analysis of meteorology and emission in haze episode prevalence over mountain-bounded region for early warning. Science of the Total Environment, 409, 2261–2271. http://doi.org/10.1016/j.scitotenv.2011.02.022

[4] Amnuaylojaroen, T., and Kreasuwun, J. (2011). Investigation of Fine and Coarse Particulate Matter from Burning Areas in Chiang Mai , Thailand using the WRF / CALPUFF Investigation of Fine and Coarse Particulate Matter. Chiang Mai Journal of Science, 39(2), 311–326.
[5] Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G Duda, X.-Y. Huang, W. Wang, and J. G. Powers, 2008: A Description of the Advanced Research WRF Version 3. NCAR Tech. Note NCAR/TN-475+STR, 113 pp. doi:10.5065/D68S4MVH
[6] Coiffier, J. Fundamentals of Numerical Weather Prediction, Cambridge University: Cambridge University Press: 2011, chapter 1.
[7] Laing, A., and J.-L. Evans, Introduction to Tropical Meteorology. Available from the NCAR MetEd website: http://www.meted.ucar.edu/tropical/textbook_2nd_edition/index.htm
[8] Wang, X., Liang, X., Jiang, W., Tao, Z., Wang, J. X. L., Liu, H., … Peckham, S. E. (2010). WRF-Chem simulation of East Asian air quality: Sensitivity to temporal and vertical emissions distributions. Atmospheric Environment, 44(5), 660–669. http://doi.org/10.1016/j.atmosenv.2009.11.011
[9] National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 2015, updated daily. NCEP GDAS/FNL 0.25 Degree Global Tropospheric Analyses and Forecast Grids. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. http://dx.doi.org/10.5065/D65Q4T4Z. Accessed† 22 Apr 2016.
[10] Macatangay, R., Bagtasa, G. and Sonkaew, T., "Finding the Optimum Resolution, and Microphysics and Cumulus Parameterization Scheme Combinations for Numerical Weather Prediction Models in Northern Thailand: A First Step towards Aerosol and Chemical Weather Forecasting for Northern Thailand". International Symposium on Grids and Clouds 2016 Academia Sinica, Taipei, Taiwan. March 13-18, 2016.
[11] Mönkkönen, P., Umac, R., Srinivasanc, D., Koponena, I. K., Lehtinena, K. E. J., Hämeria, K., Kulmala, M. (2004). Relationship and variations of aerosol number and PM 10 mass concentrations in a highly polluted urban environment — New Delhi , India. Atmospheric Environment, 38, 425–433.
[12] Stanski, H.R., L.J. Wilson, and W.R. Burrows, 1989: Survey of common verification methods in meteorology. World Weather Watch Tech. Rept. No.8, WMO/TD No.358, WMO, Geneva, 114 pp.

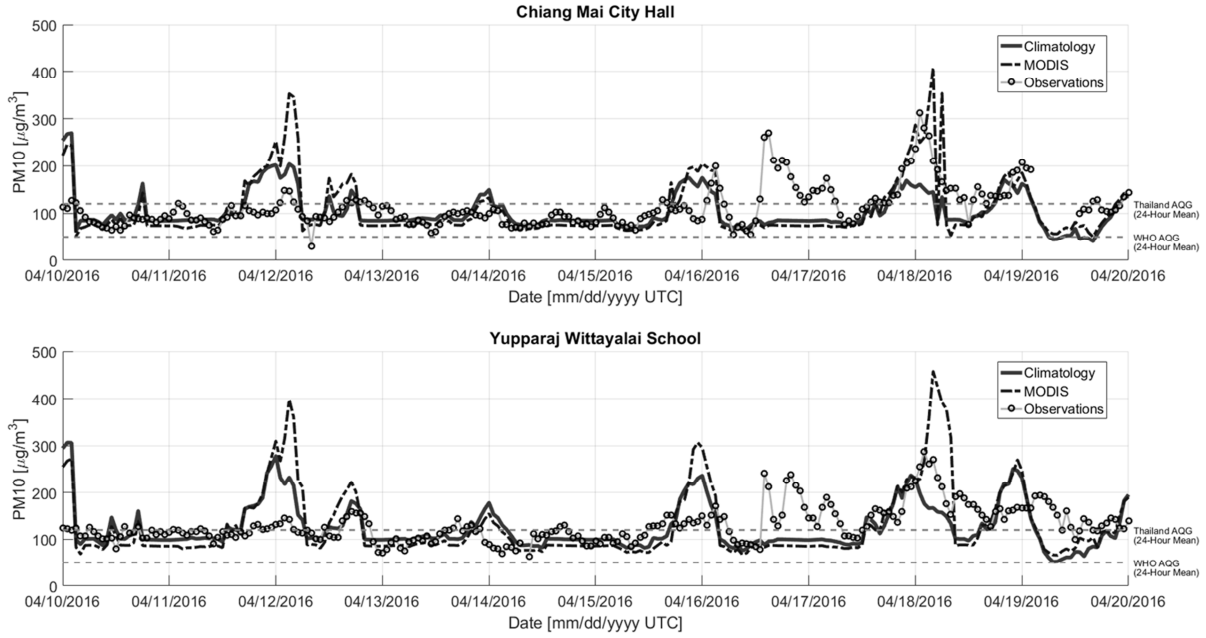

Figure 2. Simulations using the 2001-2007 GOCART climatological (solid line) and up-to-date MODIS (dashed line) aerosol number concentration boundary conditions compared to observations (circles with line) at the Chiang Mai city hall (upper panel) and Yupparaj Wittayalai School (lower panel) PCD stations (Note: the multiplicative bias calculated in Table 1 were applied for the model runs). Also shown are the World Health Organization (WHO) and the Thailand 24-Hour Mean Air Quality Guideline (AQG) value for PM10.